International Journal of Innovations in Engineering and Technology (IJIET)
http://dx.doi.org/10.21172/ijiet.141.08

Analysis of generation processes in a nanosecond low-inductive extended z-discharge

Analytical review[1]

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Abstract- The paper summarizes the results of studying the nanosecond low-inductive extended z-discharge as a source of electromagnetic radiation and analyzes the work of other research groups that can shed light on the physics of the processes revealed in the author's research. The results of the analysis are of interest in the development of compact electric-discharge coherent and low-coherent X-rays sources.

Keywords: high-current extended z-discharges, pulsed sources of EUV and soft X-ray radiation, nanosecond high-voltage discharges, gas-filled capillaries, sliding discharges, runaway electrons.

I. INTRODUCTION

For the first time, the concept of creation and the results of exploration of electric-discharge EUV and soft X-ray lasers based on the use of low-inductance extended z-discharges initially formed by a ionization wave of a sliding discharge were reported at the International Conference on X-ray Lasers in Beijing in 2004 [1]. Further experiments were carried out on the second, more powerful modification of the «Extreme» installation and were reported at X-ray conferences in Berlin, 2006 [2] and San Diego, 2007 [3]. A distinctive feature of both modifications is the use of special electrode system in close geometry that is fed through a long cable line from a pulse generator based on a double storage-forming line with a paper-oil dielectric. The double voltage propagation time in the transmitting line has been chosen approximately equal to the generation pulse duration , that equals ~ 100 ns, in order to simulate the stepped form of the incident voltage wave.

The first modification of the installation used a single cable RK-75-11-12 and a coaxial high-voltage connector for connecting a capillary load that consists of a ceramic (olund and corundum) tube with diameters of Ø5x Ø 10 mm and a coaxial return current lead with an internal diameter of 11 mm . In the unmatched mode, i.e. the case when voltage doubles, occurring at the stage of the sliding discharge, the voltage on the capillary load could reach 200 kV. In the second, more powerful modification, the transmission line consisted of eight cables is connected to the same capillary load using eight high-voltage connectors and a current-collecting coaxial node (Fig. 1).

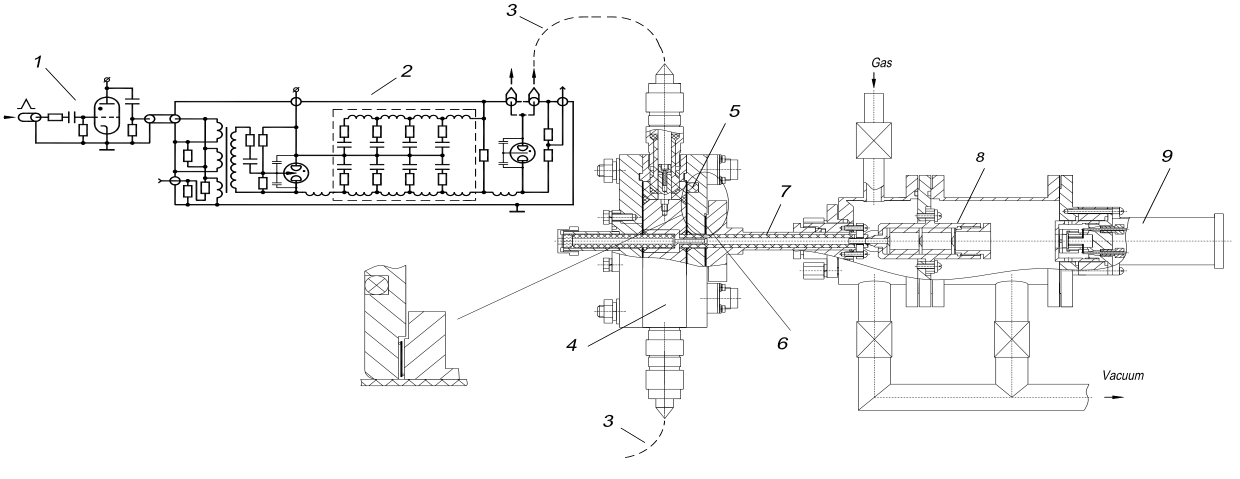


Fig. 1. The experimental setup of the second modification. 1- thyratron generator, 2- high-voltage pulse generator, 3- transport line, 4- current collector unit, 5- Rogowski coil, 6- current shunt, 7- capillary load, 8- differential gas pumping and radiation collimation unit, 9- semiconductor diode.

The maximum current in this modification could reach 23 kA in the unmatched mode, i.e. the case when current doubles, occurring at the stage of high-current discharge. Today at the Ioffe Institute RAS an experimental installation of the third modification "Extreme-M" is constructing, which can operate at currents above 50 kA. This modification is created according to the same scheme as the previous two: storage-forming lines with a paper-oil dielectric and a charging voltage of 100 kV, gas sharpeners of electrical impulses, a transmitting long line, a low-inductance discharge load with a close arrangement of electrodes and a ceramic tube with diameters 10x5 mm. Under the scope of the project it is possible to reduce the duration of the voltage front to 1 ns using a combination of different sharpeners and increase discharge currents to 100 kA by adding two more modules of storage-forming double lines with a paper-oil dielectric [4].

Due to a long time break in experimental studies related to the creation of the «Extreme-M» installation of the third modification, it is worthwhile to conduct an analytical review of studies performed by other authors on similar topics, which stimulated the writing of this work. In this review, which does not pretend to the completeness of the involved work, the results are mainly those that can shed light on the physics of the processes noted in the author's research. If readers are interested in these studies, they can found it in the references with their full output. During publication selecting for the analytical review, the keywords mentioned above were used.

2.Low-inductive extended z-discharge as a source of multiband radiation

Detailed results obtained using both installation modifications are presented in [4 - 8]; they are briefly summarized in this article to enable comparative analysis in the following sections.

1. A propagating wave of a sliding avalanche discharge, which serves as a system of preliminary ionization of gas in a low-inductance tube with a close arrangement of electrodes, was detected before the wave reached the internal cut of the output electrode and was studied, as ae subsequent z-discharge at high-current stage, by various means: a shunt for measuring the total discharge current, a voltage divider at the input of the discharge tube, photomultipliers and a coaxial photo-element with optical filters, a high-speed CCD camera type K-008, a semiconductor Si photodiode with aluminum absorbing filters for recording EUV radiation. The avalanche discharge was detected at the limit of sensitivity of the used equipment in the form of a low-luminous ring-shaped plasma formation, carrying a longitudinal current of the order of hundreds of amperes, indicating s it's avalanche nature (Fig. 2, on the left).

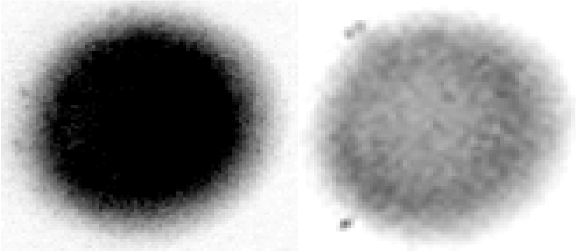


Fig. 2. Photographs of the plasma glow obtained from the end of the tube at the stage of a sliding discharge (left frame) and the z-discharge stage (right frame). p = 0.5 Torr. Uinc = 60 kV., FPS - 0.5 109 Hz.

This is confirmed by the results of a theoretical consideration of the wave propagation process based on the electric drift of electrons in the longitudinal direction and the flow of capacitive current in the transverse direction at the front of the sliding discharge and the coincidence of the calculation and experiment regarding the movement of its front depending on the initial gas pressure [6]. No soft or hard X-rays emission were observed at the incomplete stage of the sliding discharge at the pressure varied in in the range of 0.001–1000 Torr in argon; nevertheless, the ionization was sufficient to form an azimuthally symmetric extended z-discharge up to 150 mm long with a ceramic tube diameter of 5x10 mm (Fig. 2, right frame).

2. From the moment of voltage drop, associated with the development of a high-current stage, there were abrupt bursts with half-height of ~ 5 ns both of the total discharge current and the signal from the semiconductor Si diode with using EUV-SX absorbing foils (Fig. 3).

If the signal from the «protected» diode stopped after the burst, then the current signal, starting at half-height, continued for about 80-90 ns, which was caused by the continued discharge of the transmission line. It was during this period of time at low pressures (~ 0.1 Torr) that a weak, diffused EUV signal was observed, corresponding to the arrival on the axis of the discharge plasma, which was observed at the installation of the second modification, capable of producing currents up to 22 kA.

It should be noted that at pressures less than 0.1 Torr (upper oscillograms), a noticeable pre-pulse of EUV-SX) radiation appeared, associated with the sliding discharge front approaching the output electrode; also

a) during sliding discharge propagation part of the power lines start from the front, creating a local longitudinal component of the electric field. But the pre-pulse was not of interest from the point of view of creating extended radiating discharges and was easily exclude by a slight increase in pressure (above 0.1 Torr).

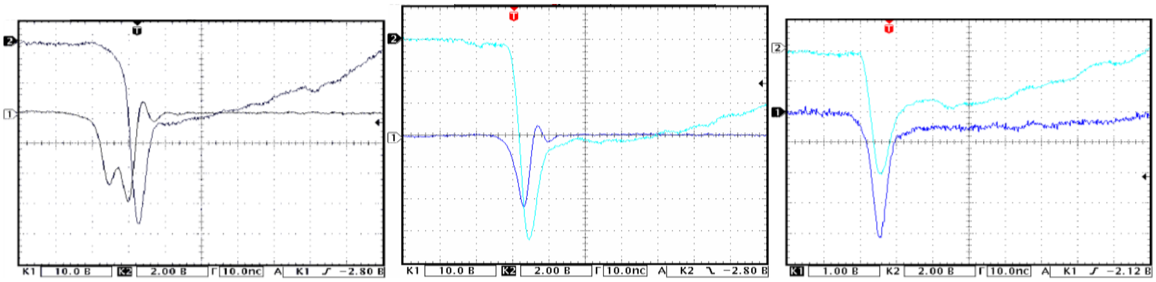


Fig. 3. Oscillograms of signals from the Si diode (1) and the total current from the foil shunt (2) for the initial gas pressure p0 = 0.08 Torr (a) and 0.2 Torr (b, c). DFL charge voltage U0 = 60 kV. The thickness of the absorbing foil is 0.8 µm (a, b), the open diode (c). The red arrows indicate the moments of the occurrence of sliding avalanche discharge.

b) The sharp bursts of EUV-SX radiation and the total discharge current were detected in a very narrow initial pressure range of 0.1–0.4 Torr of argon (the full range of research is 0.001 – 1000 Torr), which revealed the non-pinch kind. An assumption about the step-like collisional pumping of the plasma medium by runaway electrons was made: electrons gain more and more energy in a longitudinal electric field and losing it in inelastic collisions during of electrons from outer shells removal, that is result in creation a plasma of multiply charged ions.
The runaway mode occurs at the stage of high-
c) voltage high-impedance discharge, immediately following
the electrode gap closure by a sliding discharge and the preceding stage of a high-current discharge. Before this stage, the electric field configuration is changed following way: predominantly transverse component of the traveling voltage wave transverse to a longitudinal component that is not yet sufficiently shunted by a high-current discharge. At this time, the intensity of the longitudinal electric field can reach a maximum value, up to 20 kV / cm, which is enough to satisfy the well-known local criterion of electron runaway. It is important that this occurs along the entire length of the discharge tube and gives hope for the use of stimulated amplification of line radiation in an extended plasma column containing multiply charged ions.
The use of absorbing aluminum foils with a thickness of 0.8 - 4 µm showed the presence of quanta of EUV-SX emission with energy of ~ 25 eV to 1 keV, which corresponds to wavelengths from ~ 50 to 1 nm. A burst in discharge current, substantially higher than the current in the quasi-stationary part of the pulse, indicates a predominant current transfer by runaway electrons, which gain energy in a maximum longitudinal field (Fig. 3b). Direct observation of the runaway electrons could not be done, since in the space behind the end of the tube amount of runaway electrons was not within the limits of the used equipment. Due to organizational problems, unfortunately, also it was not possible to carry out spectral measurements during a burst of radiation to prove its line(or discrete) character.
3. In the conducted studies, at the initial pressure from 0.01 to 0.3 Torr, a slightly diverging hard X-ray beam with a quantum energy of 15–25 keV was found in the dead-end space according to the results obtained by the method of absorbing foils using a scintillation detector and a beryllium exhaust foil. The duration of the radiation pulse and it's maximum correspond to the duration and maximum of the quasi-stationary discharge current. With a decrease in the initial pressure, the effect of signal saturation from a scintillation detector is observed, which indicates a transition of bremsstrahlung on atoms and ions of the plasma to bremsstrahlung on wall and electrode elements.
It is surprising that all this time the voltage at capillary load is almost zero, and in this case, for the acceleration of electrons, vortex electric fields in the space of the discharge tube are necessary. They can be registered only by the contactless method, which presents great technical difficulties, and their explanation will present no less difficulties.
When shooting from the end with CCD camera with a large attenuation of the light flux, "hot spots" were obtained due to the development of plasma instabilities, the identification of which is difficult due to the lack of experimental data. Even in these conditions, the beam of hard radiation has a low divergence, less than 10-2 rad, judging by the beam imprint, obtained on an X-ray film «protected» from visible light at a distance of 5 cm from the vent. The diameter of the imprint is approximately equal to the diameter of the hole in the output tubular electrode, that equals to 3 mm (Fig. 4). The study of this phenomenon should be continued.

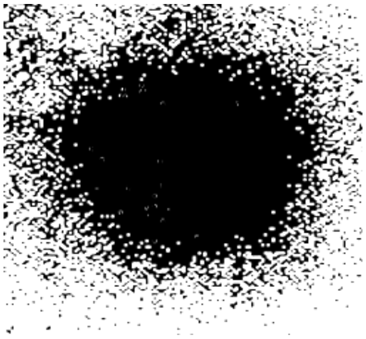


Fig. 4. The imprint of the x-ray beam on a film protected by black paper. p = 0.01 Torr.

4. The visible radiation of the plasma column was investigated in the entire range of pressure changed from 0.001 to 1000 Torr using photo amplifiers and optical filters. The presence of two broad maxima of the radiation intensity with a minimum in the region of 100 Torr was found. This is due to the transition of the discharge from the diffuse to the streamer multichannel near-wall mode, which is confirmed by images of plasma radiation taken from the tube end using the CCD camera. At lower pressures, oscillograms of signals from photoamplifiers have steep fronts with a dominant component of ultraviolet radiation. At high pressures, the oscillograms show signals with more sloping fronts with the dominant red component. The observed radiation corresponds to the quasi-stationary discharge of the transmission line.

5. At a gas pressure in the region of the atmosphere, an X-ray beam with a quantum rigidity of ~5 keV was detected using a vacuum window made of thin beryllium foil and a scintillation detector. Unfortunately, these experiments were not completed and postponed until the completion of the creation of the «Extreme» installation of the third modification, which is being constructed on the basis of the Ioffe Institute RAS [7].

6. A summary of the amplitude signals from various sensors recorded at the first modification when the initial pressure of argon is changed in the range of 0.001-1000 Torr, with inclusions of typical oscillograms for the selected pressures, is presented in Fig.5.

This picture summarizes the results of studies, some of which were repeated on the installation of the second modification. Thus, in the lower left corner, the results of the study of the amplitude dependence of EUV-SX radiation on pressure Jsx(t) and the time dependence of radiation intensity Jsx(t) are presented together with the oscillograms of the total current Icap. The form of the current clearly shows the statistical delay in the appearance of vital avalanches and the current pre-impulse of a sliding avalanche discharge with an amplitude of ~ 200 A followed by a pulse of discharge current with an amplitude of ~ 1 kA. If we compare these oscillograms with those shown in Fig. 3, it becomes clear why the sliding discharge is barely visible against the background of a current butrst with an amplitude of up to 13 kA when other transmission cables are connected.

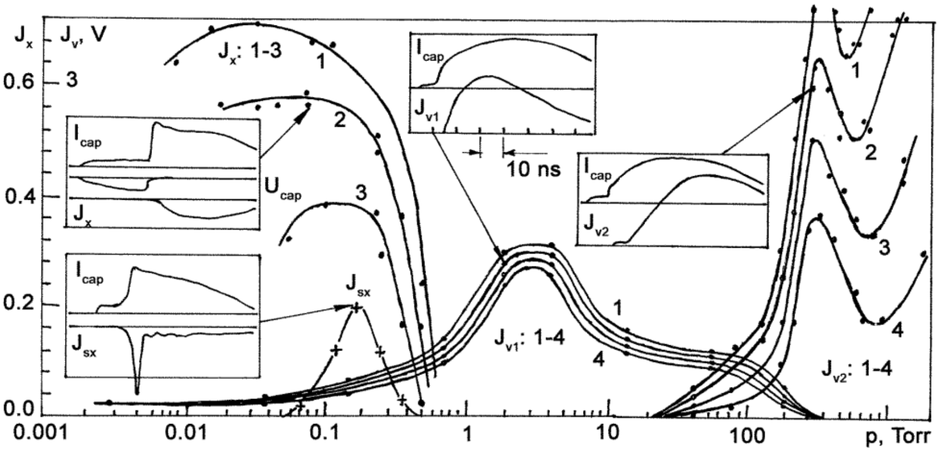


Fig.5. Dependences of the amplitudes of the first and second pulses of visible radiation Jv1, Jv2, as well as the amplitudes of pulses of hard and soft x-ray radiation Jx, Jsx, respectively, on the initial argon pressure at various incident wave voltages. Uins, kV: 1-70, 2-60, 3-50, 4-40.

Since the installation of the third modification preserves the pre-ionization system based on a sliding discharge, it is possible to compare its effectiveness and stability with increasing discharge currents up to 50-100 kA.

7. The third modification of the installation was created according to the same scheme as the first one: storage lines with a paper-oil dielectric and a charging voltage of 100 kV; diameters 10x5 mm. The project has the ability to reduce the duration of the voltage front to 1 ns, using a combination of different sharpeners and increasing discharge currents above 50 kA, adding two more modules of storage double lines with a paper-oil dielectric. This will provide an opportunity to continue researching the mechanisms without pinching to create multi-zone radiation sources. In addition, it will be possible to carry out experiments to verify the interesting results obtained by numerical studies of pinch mechanisms for creating plasma column with multiply charged ions of the desired multiplicity. These results will be published in special articles.

3.Electric discharge EUV sources and capillary tube lasers

Electric discharge compact EUV-SX lasers have become one of the main applications of extended z-discharges, which are based mainly on the use of two pumping schemes: on collisional excitation of multiply charged CEPS ions and on three-particle collisional recombination CRPS [9]. The greatest successes in the field of creating compact electric-discharge lasers were achieved in the University of Colorado, USA, under the guidance of Professor J. Rocca using the CEPS pumping scheme. So, on neon-like argon ions ArIX with a 3p-3s transition at a wavelength of 46.9 nm, table-top [10] and more compact desk-top lasers [11] were created. They were followed by a series of works with more or less successful attempts to repeat these results in Italy [12], Japan [13], Czech Republic [14], Israel [15], Russia [16] (Sarov). These lasers made it possible to carry out a number of remarkable applied research and demonstration applications, including those on EUV microscopy [17] and interference lithography [18].

However, attempts to create shorter-wavelength electric-discharge lasers, both on nickel-like cadmium ions based on CEPS with a generation wavelength $\lambda = 13.2$ nm [19], and hydrogen-like nitrogen ions based on CRPS with $\lambda = 13.4$ nm [20-22] did not lead to success. The fact is that with a decrease in the transition wavelength λ, the fundamental requirements for the magnitude of the specific pump power of the active medium Q, which is necessary to achieve the desired gain factor k, sharply increase. In the case of the Doppler broadening of the spectral line of the quantum transition, which is characteristic of electric-discharge pumping systems, the dependence of the excitation rate of the upper laser level q and the pump power on the wavelength are determined by power-law functions

$q(\lambda\text{-}3)$, $Q(\lambda\text{-}4)$

The estimates of the values of the excitation rate of the upper laser level q and the specific pump power Q for different wavelength ranges of short-wave radiation, derived from [23], made in 1977, are presented in Table 1.

λ, nm:	0,1	1	10	100
q, cm-3s-1:	1032	1029	1026	1023
Q, W cm-3:	1017	1013	109	105

It still seems impossible to find a method for solving the pumping problem in electric-discharge generation systems with a wavelength of less than 1 nm. In the region of wavelengths> 1 nm, the situation is more realistic, but it should be noted that the existing estimates take into account the energy consumption only from quantum mechanical considerations. In fact, there are many channels of loss of the input specific energy into the medium P depending on the method of its injection, making it significantly higher than the specific pump power, i.e. P> Q. In electric discharge systems based on pinching discharges, one of the most important and fundamental channels of energy consumption is the presence of large magnetic energy remaining in the system after the completion of the pumping process, which then dissipates in the discharge tube that gradually spoils the tube and shortens its service time. At 46.9 nm lasers on neon-like argon ions used a simple gas pre-ionization system using an additional μs-discharge, to facilitate the ignition of which the internal diameter of the dielectric discharge tubes is chosen to be substantially smaller than the internal diameter of the coaxial return current lead. Fig. 6 shows a typical constructional diagram of a Czech Capex laser for lasers of this type.

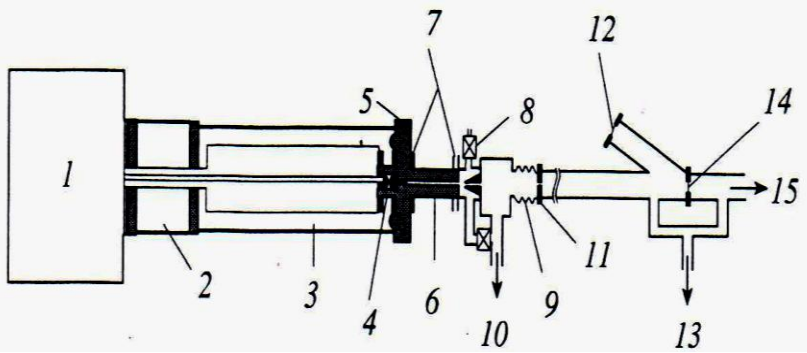


Fig. 6. Installation diagram: 1- Marx generator with oil filling, 2-electrode cavity filled with SF6, 3- fast water capacitor, 4- discharger, 5- insulator, 6- capillary, 7-Rogowski coil, 8- needle valve, 9 - sophon, 10,13- vacuum pumping, 11- diaphragm, 12- diagnostic window, 14- filter, 15- to the detector [14].

The use of inductive discharge load complicates the pumping problem, but it is not catastrophic for 46.9 nm lasers, while Q <109 W/cm3. Nevertheless, optimization of the discharge inductance is extremely important : its value should be large enough for the electric field to penetrate inside the capillary and small enough to minimize magnetic energy. An example of this optimization is the compact desk-top laser [11]. Here a sharp burst of EUV radiation occurs at the moment of the discharge compression (z-pinch), accompanied by a characteristic current dip.

The use of the general constructive scheme of 46.9 nm lasers for creation of electric-discharge 15.5 nm laser sources, requiring a significant increase in the pump power density, was unsuccessful. The service life of ceramic tubes did not reach even 10 shots, which is unacceptable for practical applications [19].

These works motivated us to make a choice in favors of low-inductance discharge tubes, which let avoid the high magnetic energy remaining in the discharge circuit after the pump pulse and subsequently released on the dielectric tube walls. We solved the problem of electric breakdown of long gaps and creation of preliminary gas ionization without the use of an additional microsecond discharge by using a propagation wave of a sliding avalanche discharge for this. The main obtained results of the studies using a similar ionization scheme are summarized in Section 2 of this article and published in detail in [4–7]. On consideration of these results the following question arises: why, in classical electric-discharge EUV lasers, a sharp burst of radiation is not observed at the current front, but only at the moment of pinching of the discharge in the region of the maximum or before the maximum of the current.

Answering this question, the main reason is the use by the authors of an additional microsecond discharge for preliminary ionization of the gas, which excluded the possibility of operating the fast capacitor as an open line with doubling the output voltage. The use of capillary tubes with an inner diameter significantly smaller than the inner diameter of the reverse coaxial current lead made it even more difficult to implement a high-voltage nanosecond discharge regime, that is responsible for the generation of runaway electrons and EUV-MR radiation. These factors led to the results described in Section 2.

The circuit features of installations of the Extreme type significantly change the operation of electric-discharge research sources, opening up new possibilities for the formation of non-pinch emitting systems, including runaway electron beams at the stage of a nanosecond discharge. For many applications (submicroscopy, interference lithography), compact electric-discharge sources of spontaneous emission will be used, for which there is no need to implement saturation modes of gain and obtain high-quality coherent radiation. Using spontaneous radiation allows you to advance into the short-wavelength range of the spectrum up to the "water window". Monochromatization of radiation from sources can be carried out using reflective mirrors with a multilayer coating [24].

As for the comparison of the results of the studies with the known electric-discharge EUV lasers operating on pinch discharges, this will be possible only after creating the third modification of the Extreme installation, capable of working both on pinch and non-pinch discharges. So far, it has been possible to compare the results with other electric-discharge systems based on the use of energy not of magnetic, but of an electric field.

4. Nanosecond sliding discharges as x-ray sources

The first works that is devoted to the similar topics, were the work of P.N. Dashuk and co-workers focused on the creation of electric-discharge radiation sources for various applications, including the photodissociation pumping of iodine lasers. The approach they developed was based on a sliding discharge for the electrical breakdown of long gaps in electrically strong gas media and the formation of large-area radiating surfaces. So, in a pioneering work

[25] they first experimentally recorded x-ray radiation of a single-channel sliding discharge in air at atmospheric pressure in the form of two spikes (Fig. 7).

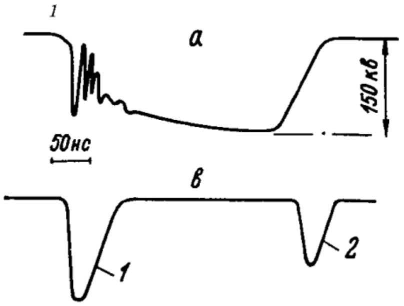


Fig.7. Oscillograms of pulse voltage, supplied on discharge gap pwith length of 20 sm (a) and x-ray (б). [25].

We used a voltage pulse generator with an amplitude of up to 170 kV with a front of 3 ns, a duration of 350 ns, and an energy reserve of 1J. The generator consisted of a shaping line and a surge arrester responsible for the first X-ray pulse with a stiffness of up to 6-7 keV.

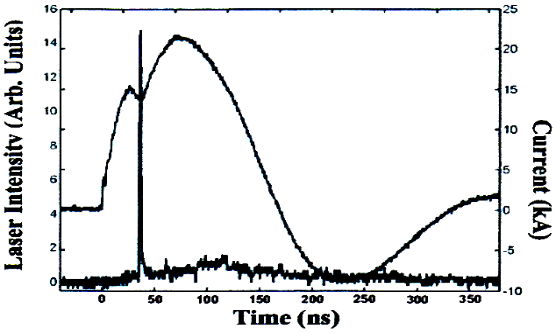


Fig. 8. Discharge current (upper track), laser EUV signal (lower track) [11]

We did not observe such a phenomenon, since the transmission line was connected to a coaxial load to initiate a traveling wave of a sliding avalanche discharge, and there was no longitudinal field component from the very beginning. The second peak in Fig. 7 appeared after the discharge gap was closed by a ionization wave of a sliding discharge and the configuration of the electric field with the predominant longitudinal component was rearranged, which leads to the appearance of highly energetic electrons with an energy of ~ 7.5 keV and the corresponding bremsstrahlung. This is agree with the data from our work described the role of tuning the configuration of the electric field in the formation of a high-voltage nanosecond discharge and a runaway electron beam under condition satisfying of the runaway criterion (7-10) 104 V/ (cm.atm) for most gases [27].

In other work of the same authors [26] the results of researches for source of x-ray radiation generated by a nanosecond sliding discharge in an atmospheric air and other gases. In this work, as in the previous publication, we used a voltage pulse generator with an amplitude of up to 170 kV, with a front of the order of 1 ns and an energy reserve of 1 J. The study of plasma propagation velocity (up to the moment when plasma shorts the discharge gap) at the pressure 0.01-1000 Torr showed that the maximum speeds are observed at pressures close to atmospheric, i.e. (3-7)109 cm /s. |It disagrees with our data [1–7], according to which the maximum propagation velocity of an avalanche discharge is observed at pressures slightly less than 10 Torr, when the maximum speed of the electric drift of electrons along the dielectric surface is reached. Moreover, this speed decreases both with decreasing and increasing gas pressure, which corresponds to the calculations performed by our proposed method. Obviously, in the work of P.N. Dashuk's plasma propagation speed was determined by the later moments of the development of the sliding discharge. Indeed, in the region of high pressures above 100 Torr, according to the data of [4–7], a second maximum was observed, which confirms the made assumption.

In general, the work [27] is more devoted to the study of a completed sliding discharge and its ability to generate x-ray radiation. After the moment discharge overlaps the interelectrode gap, the current and voltage oscillograms become typical for gas discharges, while the x-ray intensity assumes a two-hump form where there is the humps correlate with features on the discharge current oscillograms. It is interesting to note that in our studies when we study the radiative characteristics of a low-inductance discharge also in a wide range of 0.001-1000 Torr, we noticed a change in the nature of the completed sliding discharge from diffuse to streamer one in the region of 100 Torr.

Moreover, the time dependence of the ultraviolet component also has a two-hump shape where the second hump moving toward the first one with approaching of 100 Torr. This transient pressure value also appears in [27], when the energy and radiative characteristics of discharges with a wide pressure variation are discussed. The fact that at high pressures the dose of x-ray radiation falls and the minimum length of the short-wavelength radiation increases is understandable, since the fraction of the introduced energy per one particle decreases.

Generation of x-ray radiation starts from the moment the sliding discharge shorts the gap and continues for 10-18 ns at low pressures and for 3 ns at high pressures. The thing is that the temporary constant is greater at low pressures. It agrees with our assumption about the role of the non-stationary high-voltage discharge stage that occurs immediately after a sliding discharge shorts a gap ¸ when the voltage is not yet shunted by an expanding longitudinal discharge. It is this “high-voltage” discharge that causes the runaway electrons and x-ray radiation, and not the sliding discharge, especially at an incomplete stage.

It should be noted that in the cited works, the term sliding discharges is used by the authors in a broader sense, referring to them as incomplete and completed stages, although the second stage would be more correct to relate to a high-voltage self-maintained discharge.

In the next work [28], the results of experiments on the formation of an electron beam in a plasma of a sliding discharge in cylindrical geometry are presented. In the experiments the same high-voltage pulse generator is used, but the discharge chamber was a tube with an outer diameter of 60-100 mm, an inner diameter of 5-40 mm, a length of 10-180 mm, and a coaxial reverse current lead. The experimental conditions are close to ours, except that we use a low-inductance ceramic tube with diameters of 5x10 mm and a length of 50-150 mm, and also use a rather heavy gas - argon, which under certain conditions can form a plasma of multiply charged ions. In this work, a light gas, helium, was used, and therefore EUV-MR was not observed. The main goal of the work was to obtain a beam of accelerated electrons in a plasma of a sliding discharge, rather than an EUV.

The studies revealed the formation of a beam of electrons accelerated to energies of tens of keV with a current of up to 4 kA, which carry an almost complete discharge current in the tube volume. The effect of self-focusing of an electron beam up to a diameter of ~ 1 mm was experimentally discovered, which is possible provided that the space charge of accelerated electrons is neutralized. The optimal length of the discharge gap for obtaining the largest current amplitude of accelerated electrons was also found. At shorter lengths, the well-known regime of a gas-filled diode occurs, which is developed at the IHCE, Tomsk, and VNIIEF, Sarov, which will be discussed in the next section. At large lengths, an extended z-discharge regime should arise with the formation of a column of plasma of multiply charged ions and the generation of EUV radiation using multi-shell atomic gases, as in our experiments. The energy of accelerated electrons in this case is invested to the ionization and excitation of such gases along the entire length of the tube and can be the basis for the creation of electric-discharge lasers, - it is that idea we developed.

In [29], the results of the use of a sliding discharge MR emission to produce photoelectrons at distances up to 300 mm from a radiating large surface are presented. The concentration of electrons in the gas volume, located at a distance of 10-300 mm from the output plane of the emitter, was detected by the current flowing between two flat electrodes. The conducted studies allowed the authors to propose a method for calculating the X-ray spectrum of a nanosecond sliding discharge from the experimentally obtained dependence of the concentration of photoelectrons on the distance to the radiation source by measuring the photocurrent to the collector electrode.

The made calculations make it possible to determine the dependence of the spectral density of the radiation flux on the wavelength; the maximum density was observed at λ ~ 0.8 nm (Fig. 9). The obtained results are in good agreement with the data from our works [4–7] obtained by the method of absorbing foils.

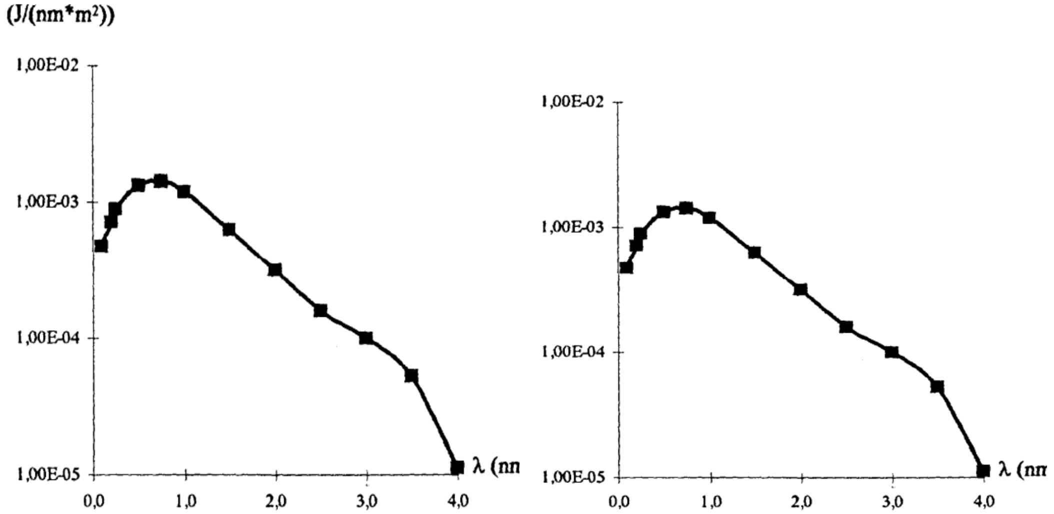


Fig. 9. The dependence of the spectral density flux of the radiation flux the on the wavelength.

The work [30] is devoted to a direct experimental study of the spectrum of x-rays from a gas discharge with runaway electrons at low xenon pressures, as well as oxygen with a vanadium target. This work differs from Dashuk's series of the topic of nanosecond sliding discharges, but is given here, since it is devoted to the development of a method for the direct study of X-ray spectra using an energy-dispersive registration system. The system was based on the Amptek Inc. semiconductor detector Si-Pin Si (Li) calibrated using a standard 55Fe γ-source. The experiments were carried out in low-current discharges (up to 30 mA), which made it possible to record both bremsstrahlung and characteristic X-ray radiation associated with the type of gas in the discharge chamber and its structural elements. This should be kept in mind in case of studying high-current discharges with runaway electrons and their interaction with chamber walls and electrodes, especially at low initial pressures (see paragraph 2 of Section 2).

5.High voltage nanosecond discharges in gas-filled diodes as a runaway subnanosecond electron beam sources

The work of Dashuk's group is very close to the works with low-inductance extended z-discharges and their comparative analysis is useful for a better understanding of the physics of sliding and subsequent high-voltage discharges and their radiative characteristics. At the same time, the work carried out at IHCE, VNIIEF, IEP UD RAS was mainly aimed at obtaining nanosecond and subnanosecond runaway electron beams in gas-filled and vacuum diodes with short electrode gaps.

The most developed nanosecond gas-filled atmospheric pressure diodes are simple and have numerous applications, but their physics is quite complex and not yet fully understood, which is confirmed by numerous publications, including a review [31, 32, 33] and a discussion one [34, 35]. Let us leave aside the discussion of runaway criteria (it deserves a separate consideration) and present a formula convenient for practical applications for estimating the critical field [31]

$Ecr/p=3.38^{\cdot}\ 103z/I$,

where I is the average energy of inelastic electron losses (for example, for nitrogen z = 14, I = 80 eV, Ecr/p = 590 V / (cm.Torr)); this formula works for most ns discharges. Let us dwell in more detail on the issue related to the physics of runaway electrons which we discovered at the Extreme installations.

It is known that in a low-temperature, weakly ionized gas-discharge plasma electrons acquire the energy of directional motion from an electric field and spend it on ionization and excitation of neutral particles. At high ratios of the field strength to the initial gas pressure, the energy acquired by the electron along the mean free path can exceed the energy given in inelastic collisions, and the electron changes to continuous acceleration mode. In the case of sufficiently short electrode gaps, accelerated electrons pass through the anode space and can be used in various applications. In these works, emission processes at the cathode are of great importance, affecting the regime of continuous electron acceleration.

In extended z-discharges we also observed X-rays in the space behind the anode with an average quantum energy of ~ 5 keV, which, obviously, were a consequence of the deceleration of runaway electrons in argon at atmospheric pressure (see point5 of the first section). Unfortunately, we postponed these experiments, and the main attention was

paid to low-pressure discharges, more promising for the creation of coherent radiation sources. This is what determined the selection of further publications for an analytical review of the generation processes in z-discharges.
The study of the formation of subnanosecond current pulses of an electron beam in a gas diode at low pressures is the subject of [36].

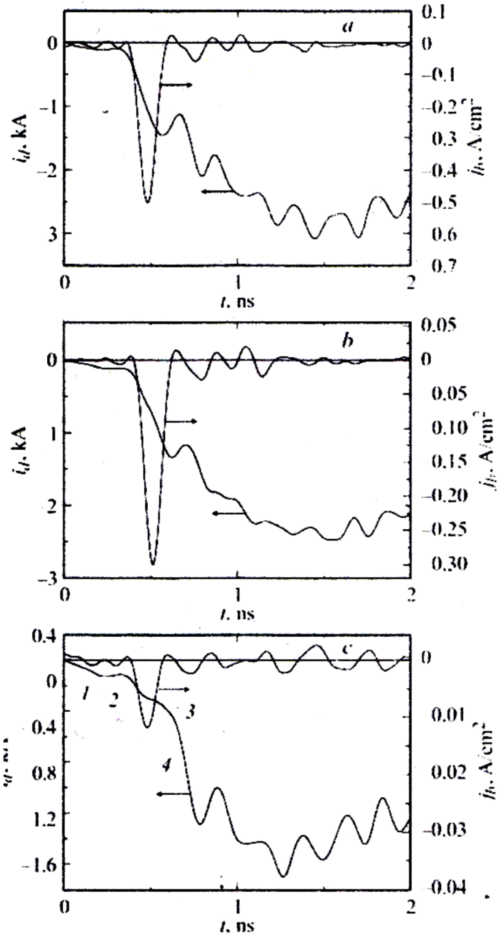


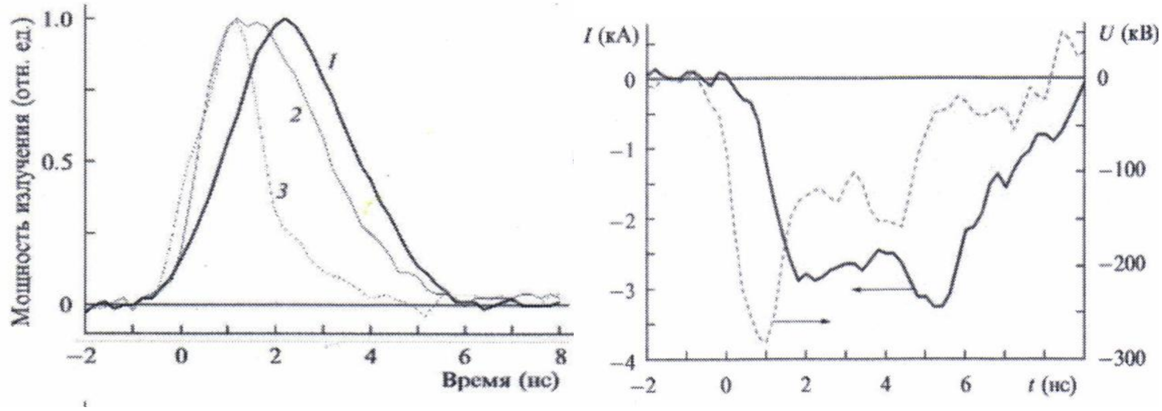
Fig. 10. Oscillograms of discharge current and runaway electron current at nitrogen pressures 350 (a), 700 (b), 2100 (s) Torr. The gap is 12 mm. [36].

The experiments showed [10], that with a decrease in the initial pressure, starting from a certain value depending on the type of gas (various gases were used, including argon), the amplitude of the beam current behind the foil and the pulse duration at half maximum increased. At a pressure of the order of several Torr, the generation of a subnanosecond avalanche beam is disrupted and the vacuum diode mode occurs. Note that the diameter of the foil cathode was 6 mm with a cathode – anode gap of 14 mm. Comparing these results with our results obtained at a pressure of less than 1 Torr, we can say that the tendency to increase the beam current and its duration is similar to the tendency to increase the yield of the scintillation detector with decreasing pressure. But all this is strongly shifted towards lower pressures; So, at pressures greater than 0.4 Torr, there are no signals from our EUV sensor, and the transition to the vacuum diode mode in our case occurs at pressures less than 0.1 Torr. A photograph of the film’s luminescence under the influence of an electron beam (the size of the luminescence nucleus is ~ 1 mm) is very similar to the X-ray trace on the RF-3 film (Fig. 4).
The authors of [37] reported the results of a study of a diffuse discharge formed in an inhomogeneous electric field at elevated nitrogen pressures using a runaway electron beam. In this work, we paid attention on recording the fronts of the total discharge current and sharp bursts of the extracted runaway electron currents connected to these fronts and contributing to the transfer of discharge currents (Fig. 9). The effect almost disappears at pressures above three atm. and increases with decreasing pressure. A previous work reported the discovery of a maximum current density of the extracted beam at even lower pressures, more precisely, at ~ 30 Torr, after which the current decreases sharply [36]. Unfortunately, in this work there are no data for pressures in the average range of 0.1 - 30 Torr. It was

in this range that we observed the maximum runaway electron current, judging by their contribution to the total discharge current in the region of the sharp burst, and the pronounced peak of the EUV radiation (Fig. 3)

The formation of a sharp burst of runaway electrons at the current front and subsequent high-current discharge is called the volume discharge initiated by the beam of the electron avalanches(VDIBEL). This discharge was used by a group of V.F. Tarasenko for generation in the UV, IR and visible spectral regions [38–40]. The mechanism of electric discharge pumping is very similar to the method used in IR laser physics and technology for pumping molecular media by a volume discharge controlled by an electron beam or X-ray flux. But to the authors' justification, it is implemented in the nanosecond, and not the microsecond, range of the pump time, and this is of great importance. Although its essence remains the same: penetrating radiation serves to ensure the volume e discharge, and energy pumping is nevertheless provided by the discharge itself.

This is demonstrated by the oscillograms shown in Fig. 11: “useful” pumping occurs after a voltage peak, when a runaway electron beam is formed. The advantage of this approach to the formation of a self-sustained volume discharge is that there is no need for a source of additional ionization. Also important is the possibility of increasing the pressure of the working gas. With an increase in the pump power, in principle, there is the prospect of reaching the EUV-MR range if it is possible to obtain a stable and uniform plasma cord from multiply charged ions.



a) b)

Fig.11. Oscillograms of current and voltage of discharge in nitrogen at pressure of 1 atm (a) and laser radiation (b) at different gas pressures. P=0,4 atm (1), 1 atm (2), 1,6 atm (3).

In our case, a slightly different situation is observed. At the stage of the high-voltage nanosecond high-impedance discharge, a runaway electron beam is generated, which pumps an extended plasma cord with a colliding non-pinch mechanism. The interaction of stepwise runaway electrons with the filling gas is so effective that they are not detected behind the tube section. Inside the tube, the runaway effect is confirmed by the strong contribution of accelerated electrons to the total discharge current in the form of a sharp burst with a record amplitude in comparison with the known Tomsk experimental data (~ 13 kA vs. ≥1 kA).

6. Conclusion

The analysis of the phenomena detected at the Extreme experimental facilities using the results obtained on other types of electrophysical installations has basically confirmed the preliminary conclusions made earlier regarding various mechanisms of radiation generation, including those based on the electron runaway effect. The remaining doubts and misunderstandings regarding, in particular, non-pinch mechanisms for pumping active media and their effectiveness, can be dispelled after spectral studies of plasma cords in a third modification to confirm the linear nature of short-wave radiation. The results of the analysis are of interest in the development of compact electric-discharge sources of coherent, weakly coherent, and spontaneous emission of the EUV-MR-HR spectral ranges.

The author is grateful to V.I. Chernobrovin and E.P. Bolshakov for participating in the experimental work and N.V. Kalinin for useful discussions.

This work was supported by the Russian Federal Property Fund, grants No. 11-08-01100, 12-08-01028, 14-08-01166, 15-08-0241066, 18-08-01066.

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